

The peculiar 2011 outburst of the black hole candidate IGR J17091–3624, a GRS 1915+105 like source?

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ABSTRACT

We report on the long-term monitoring campaign of the black hole candidate IGR J17091–3624 performed with *INTEGRAL* and *Swift* during the peculiar outburst started on January 2011. We have studied the two month spectral evolution of the source in detail. Unlike the previous outbursts, the initial transition from the hard to the soft state in 2011 was not followed by the standard spectral evolution expected for a transient black hole binary. IGR J17091–3624 showed pseudo periodic flare-like events in the light curve, closely resembling those observed from GRS 1915+105. We find evidence that these phenomena are due to the same physical instability process ascribed to GRS 1915+105. Finally we speculate that the faintness of IGR J17091–3624 could be not only due to the high distance of the source but to the high inclination angle of the system as well.

Key words: X-rays:binaries – accretion discs – Methods: observational

1 INTRODUCTION

The Black Hole Candidate (BHC) IGR J17091–3624 was discovered by *INTEGRAL*/IBIS during a Galactic Centre observation on 2003 April 14–15 (Kuulkers et al. 2003). At the onset of the discovery outburst, the source showed a hard spectrum with a flux of about ~ 20 mCrab in the 40–100 keV energy range. The analysis of IBIS, JEM-X, and *RXTE*/PCA data of the whole outburst (Capitanio et al. 2005; Lutovinov & Revnivtsev 2003; Lutovinov et al. 2005) revealed an indication of a hysteresis-like behaviour. The presence of a hot disc blackbody emission component during the softening of the X-ray emission of the source was also unveiled.

After the *INTEGRAL* discovery, IGR J17091–3624 was searched in the archival data of both TTM-KVANT (Revnivtsev et al. 2003) and *BepoSAX*/WFC (in ’t Zand et al. 2003). In the former archive, one outburst was discovered dating back to 1994 and reaching a flux of 10 mCrab in the 3–30 keV energy band; the analysis of *BeppoSAX*/WFC data revealed that a second outburst had occurred in 2001, reaching a flux of $14 \div 20$ mCrab (2–10 keV).

IGR J17091–3624 lies at $9.6'$ from another transient X-ray binary, IGR J17098–3628, discovered on 2005 March 24 (Grebenev et al. 2005) when it underwent a 4 year long outburst (Capitanio et al. 2009a). On 2006 August 29 and 2007 February 19, two *XMM-Newton* observations of the region around these two sources were performed. While IGR J17098–3624 was detected

in a relatively bright state in both observations, IGR J17091–3624 was not detected and an X-ray upper limit of 7×10^{32} erg s^{−1} was obtained (assuming a distance of 8 kpc; Capitanio et al. 2009a).

The refined position of IGR J17091–3624 provided by Kennea & Capitanio (2009) ruled out the tentative radio counterpart previously proposed for the source (Rupen et al. 2003; Pandey et al. 2006). A re-analysis of the archival radio observations performed 9 days after the source discovery by IBIS in 2003, enabled the identification of a faint transient radio source (sub-mJy level at 5 GHz) that showed a flux increase in the subsequent two weeks and an inverted spectrum, a signature of a compact jet (Capitanio et al. 2009a). This was consistent with the Low/Hard spectral state (hereafter LHS) observed by *INTEGRAL* in the same period (Capitanio et al. 2005). The source behaviour during the 2007 observation campaign was typical of a BHC in outburst, even if the relatively low X-ray flux of the source (0.5–10 keV peak flux of $\sim 2 \times 10^{-9}$ erg cm^{−2} s^{−1}) hindered a detailed spectral evolution study (Capitanio et al. 2009a).

At the end of January 2011 the *Swift*/BAT hard X-ray transient monitor reported a renewed activity from IGR J17091–3624. The source flux increased from 20 mCrab on January 28 up to 60 mCrab on February 3 in the energy range 15–50 keV (Krimm et al. 2011; Krimm & Kennea 2011). The corresponding XRT spectrum obtained with a ToO observation was well described by an absorbed power law with a photon index of 1.73 ± 0.29 (Krimm & Kennea 2011). On 2011 February 7, the region around IGR J17091–3624 was also observed by the IBIS/ISGRI and JEM-X telescopes on board the *INTEGRAL* satellite. The estimated source flux in the 20–100 keV energy range was 120 mCrab. The combined ISGRI+JEM-

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X spectrum (5-200 keV) could be well described by an absorbed cut-off power law model with a photon index of ~ 1.4 and a high energy cutoff of about 110 keV. This suggested that the source was in LHS (Capitanio et al. 2011).

Follow-up radio observations carried out with the ATCA telescope measured a flat spectrum (Torres et al. 2011; Corbel et al. 2011; Rodriguez et al. 2011b) associated with self absorbed compact jets, as expected in accreting black holes in the LHS. Later on, Rodriguez et al. (2011b) reported also on the detection of a discrete jet ejection event usually observed when a BHC undergoes a transition from the Hard Intermediate State (hereafter HIMS) to the Soft Intermediate State (hereafter SIMS). A 0.1 Hz QPO, increasing in frequency with the source flux and spectral softening, was revealed by both Rodriguez et al. (2011a) and Shaposhnikov (2011). These findings motivated a long monitoring campaign that was carried out with *Swift*/XRT, starting on February 28. The XRT observations were planned to be simultaneous with the *INTEGRAL* pointings already scheduled in the direction of the source, in order to ensure the broadest possible energy coverage (0.3-200 keV) during the entire outburst.

As reported by Del Santo et al. (2011), on February 28 the XRT+IBIS joint spectrum resulted in a typical High Soft State (HSS) shape, with a prominent disc black body component ($kT_{in} \sim 1$ keV) and a power-law photon index of 2.2 ± 0.2 . No high-energy cut-off was present up to 200 keV. On 2011 March 14 (MJD 55634) a ~ 10 mHz QPO was detected in a 3.5 ks *RXTE* observation (Altamirano et al. 2011b). One week later, *RXTE*/PCA showed a continuous progression of quasi-periodic flare-like events occurring at a rate between 25 and 30 mHz. This kind of variability resembles the “heartbeat” variation observed in the Black Hole (BH) binary GRS 1915+105 (Altamirano et al. 2011c; Pahari et al. 2011a,b). Altamirano et al. (2011d) reported a detailed study of the behaviour of the flare-like events of IGR J17091–3624 during the first 180 days of the outburst. This study classified the different types of flares with the same scheme used by Belloni et al. (2000) for GRS 1915+105.

In this paper we report on the *Swift* and *INTEGRAL* data analysis of the new outburst of IGR J17091–3624 started at the end of January 2011.

2 DATA REDUCTION AND ANALYSIS

The XRT ToO follow-up observations were performed, when possible, simultaneously to the *INTEGRAL* ones (Capitanio et al. 2011). *INTEGRAL* data were collected in the framework of the Galactic bulge observations¹ (public data) and the open time observation of the RX J1713.7-3946 field. Due to the long duration of the outburst, *Swift*/XRT data were collected also in the period in which the region around IGR J17091–3624 became unobservable by *INTEGRAL*. In this paper we made use of the whole available data set of *INTEGRAL* and *Swift* observations performed from 28 January to 14 August 2011.

The XRT observations were taken in window timing mode in order to avoid the pile-up effects. Each observation was composed of two or more segments. We reported only the analysis of the first segments of all XRT observations, since the other segments were always consistent with the first segments of each observation. For the XRT data analysis we followed standard pro-

cedures (Burrows et al. 2005) and the technique summarized in Bozzo et al. (2009). XRT light curves and the hardness-intensity diagrams were obtained from the XRT data extracting two different energy ranges, 0.3-4 keV and 4-10 keV.

For the *INTEGRAL* data analysis, we used the latest release of the standard Offline Scientific Analysis, OSA version 9.0, distributed by the ISDC (Courvoisier et al. 2003) and the latest response matrices available. In particular, the IBIS response matrices were produced using the closest available Crab observations to the 2011 outburst of IGR J17091–3624. Our *INTEGRAL* analysis was focused on ISGRI (Lebrun et al. 2003), the low-energy detector of the γ -ray telescope IBIS (Ubertini et al. 2003) and on the X-ray monitor JEM-X (Lund et al. 2003). Unfortunately, due to the *INTEGRAL* observing strategy combined to the small JEM-X field of view (FOV), IGR J17091–3624 was not in the JEM-X FOV in most of the observations. During the *INTEGRAL* observations both JEM-X modules were switched on. However, for the data analysis we used the second module (JEM-X2) and checked the consistency with module 1. The ISGRI and JEM-X spectra were extracted in 20-200 keV and 3-20 keV, respectively. A systematic error of 2% was taken into account for spectral analysis (see also Jourdain et al. 2008).

Details on all the *Swift* and *INTEGRAL* data analysed in this paper are given in Table 1 (columns 1-4). The spectral and timing analysis have been performed with HEASOFT 6.9 package. In particular, the periods of the flare-like events were calculated with the FTOOL *efsearch*. The *rms* values were estimated from the source light-curves by using an *ad hoc* developed tool and the *IDL Astronomy User's Library procedures*². For the *rms* calculation, we divided the light curves, extracted in 1 s bins, into 140 s chunks. For each segment we computed the fractional *rms* after subtracting the expected white noise. We then estimated the fractional *rms* of the light curves and its uncertainty from the average and standard deviation of the single determinations. The effective frequency range over which the *rms* is integrated is therefore 0.007-0.5.

¹ <http://integral.esac.esa.int/BULGE>

² <http://idlastro.gsfc.nasa.gov/>

Table 1: Observations log and spectral parameters of the outburst evolution. Note: all the errors are at 90% confidence level. N is the label of each XRT observation associated to the points of Figure 11 and Figure 5; ID is the XRT observation number; Date is the date of the XRT observation; rms is the value of the root-mean-square amplitude of each XRT observations averaged in an interval between 0.007 and 0.5 Hz. *INTEGRAL* REV indicates, when available, the revolution number of *INTEGRAL* simultaneous observations; T_{in} is the inner temperature of the *diskbb* model in XSPEC; NORM *diskbb* is the normalization of the *diskbb* model proportional to the square of the inner disc radius square; Γ is the power law photon index and E_c is the high energy cut off; $FLUX_{(2-10)keV}$ is the unabsorbed flux between 2 and 10 keV.

| N | ID | Date | XRT EXP | <i>INTEGRAL</i> | rms | T_{in} | NORM | Γ | E_c | $FLUX_{(2-10)keV}$ | $\chi^2_{red}(d.o.f.)$ |
|----|-------------|---------|---------|-----------------|-------------------|-------------------------|--------------------|-------------------------|--------------------|--|------------------------|
| - | - | MJD | s | REV | cnt | keV | <i>diskbb</i> | - | keV | ($\times 10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1}$) | - |
| 1 | 00031921002 | 55598.3 | 1940 | 1016 | 0.29 \pm 0.08 | - | - | 1.4 $^{+0.1}_{-0.1}$ | 109 $^{+28}_{-19}$ | 6.1 | 1.0(139) |
| 2 | 00031921003 | 55599.2 | 2170 | 1016 | 0.28 \pm 0.03 | - | - | 1.5 $^{+0.1}_{-0.1}$ | 120 $^{+30}_{-21}$ | 6.5 | 1.0(193) |
| 3 | 00031921004 | 55600.7 | 2175 | 1016 | 0.25 \pm 0.07 | - | - | 1.5 $^{+0.1}_{-0.1}$ | 104 $^{+19}_{-14}$ | 6.8 | 1.0(164) |
| 4 | 00031921005 | 55601.1 | 1454 | - | 0.25 \pm 0.06 | - | - | 1.5 $^{+0.1}_{-0.1}$ | - | 6.1 | 0.8(175) |
| 5 | 00031921006 | 55602.1 | 2191 | 1017 | 0.21 \pm 0.03 | - | - | 1.6 $^{+0.1}_{-0.1}$ | 125 $^{+31}_{-21}$ | 9.3 | 1.0(174) |
| 6 | 00031921007 | 55603.2 | 2066 | 1017 | 0.24 \pm 0.06 | - | - | 1.5 $^{+0.1}_{-0.1}$ | 86 $^{+11}_{-9}$ | 8.6 | 1.0(210) |
| 7 | 00031921008 | 55604.2 | 2189 | 1017 | 0.27 \pm 0.03 | - | - | 1.5 $^{+0.1}_{-0.1}$ | 93 $^{+11}_{-9}$ | 9.4 | 1.3(264) |
| 8 | 00031921009 | 55605.2 | 2163 | 1018 | 0.24 \pm 0.07 | - | - | 1.5 $^{+0.1}_{-0.1}$ | 86 $^{+35}_{-21}$ | 10.0 | 1.1(200) |
| 9 | 00031921010 | 55606.2 | 1884 | - | 0.22 \pm 0.03 | - | - | 1.6 $^{+0.1}_{-0.1}$ | - | 8.6 | 1.1(139) |
| 10 | 00031921011 | 55607.2 | 2108 | - | 0.24 \pm 0.05 | - | - | 1.6 $^{+0.1}_{-0.1}$ | - | 8.9 | 1.1(217) |
| 11 | 00031921012 | 55608.3 | 2057 | - | 0.22 \pm 0.02 | - | - | 1.61 $^{+0.04}_{-0.04}$ | - | 9.1 | 1.1(249) |
| 12 | 00031921013 | 55610.2 | 2010 | - | 0.21 \pm 0.03 | - | - | 1.6 $^{+0.1}_{-0.1}$ | - | 10.4 | 1.0(225) |
| 13 | 00031921014 | 55612.3 | 2095 | 1020 | 0.15 \pm 0.05 | - | - | 1.69 $^{+0.04}_{-0.04}$ | 75 $^{+9}_{-7}$ | 14.7 | 1.0(311) |
| 14 | 00031921015 | 55614.2 | 2195 | 1020 | 0.08 \pm 0.04 | 0.3 $^{+0.1}_{-0.1}$ | < 1×10^5 | 2.0 $^{+0.1}_{-0.1}$ | 134 $^{+43}_{-29}$ | 20.5 | 1.2(366) |
| 15 | 00031921016 | 55616.3 | 1074 | - | 0.05 \pm 0.02 | 1.1 $^{+0.1}_{-0.1}$ | 53 $^{+38}_{-24}$ | 2.1 $^{+0.3}_{-0.5}$ | - | 20.6 | 1.1(322) |
| 16 | 00031921017 | 55620.8 | 2568 | - | 0.06 \pm 0.02 | 1.0 $^{+0.1}_{-0.1}$ | 54 $^{+35}_{-25}$ | 2.1 $^{+0.2}_{-0.2}$ | - | 17.8 | 1.0(428) |
| 17 | 00031921018 | 55622.5 | 2321 | - | 0.09 \pm 0.03 | 1.0 $^{+0.2}_{-0.1}$ | 46 $^{+63}_{-37}$ | 2.1 $^{+0.3}_{-0.4}$ | - | 19.5 | 1.2(268) |
| 18 | 00031921019 | 55623.5 | 656 | - | 0.05 \pm 0.02 | 1.1 $^{+0.2}_{-0.1}$ | 54 $^{+41}_{-27}$ | 2.1 $^{+0.3}_{-0.4}$ | - | 18.2 | 1.1(316) |
| 19 | 00031921020 | 55624.4 | 2463 | - | 0.05 \pm 0.02 | 1.1 $^{+0.1}_{-0.1}$ | 60 $^{+18}_{-18}$ | 1.7 $^{+0.3}_{-0.7}$ | - | 18.9 | 1.1(443) |
| 20 | 00031921021 | 55627.6 | 2072 | 1025 | 0.04 \pm 0.02 | 1.3 $^{+0.1}_{-0.1}$ | 49 $^{+24}_{-14}$ | 2.4 $^{+0.1}_{-0.1}$ | - | 35.1 | 1.0(433) |
| 21 | 00031921022 | 55628.1 | 1706 | 1025 | 0.05 \pm 0.02 | 1.29 $^{+0.04}_{-0.04}$ | 98 $^{+56}_{-30}$ | 2.4 $^{+0.2}_{-0.1}$ | - | 47.6 | 1.1(489) |
| 22 | 00031921023 | 55630.5 | 1408 | - | 0.05 \pm 0.02 | 1.03 $^{+0.04}_{-0.04}$ | 90 $^{+13}_{-19}$ | 1.3 $^{+0.5}_{-0.1}$ | - | 17.1 | 1.2(401) |
| 23 | 00031921024 | 55632.3 | 2189 | 1027 | 0.07 \pm 0.02 | 1.29 $^{+0.04}_{-0.04}$ | 71 $^{+33}_{-21}$ | 2.6 $^{+0.1}_{-0.1}$ | - | 40.3 | 1.0(411) |
| 24 | 00031921025 | 55633.3 | 2016 | - | 0.08 \pm 0.06 | 1.31 $^{+0.02}_{-0.02}$ | 51 $^{+4}_{-4}$ | - | - | 18.2 | 1.2(357) |
| 25 | 00031921026 | 55635.6 | 1473 | 1028 | 0.07 \pm 0.03 | 1.2 $^{+0.1}_{-0.1}$ | 35 $^{+12}_{-8}$ | 2.1 $^{+0.1}_{-0.1}$ | - | 15.2 | 1.2(434) |
| 26 | 00031921028 | 55639.8 | 2225 | - | 0.27 \pm 0.02 | 1.28 $^{+0.03}_{-0.03}$ | 63 $^{+20}_{-26}$ | - | - | 20.7 | 1.0(274) |
| 27 | 00031921029 | 55638.6 | 2155 | - | 0.10 \pm 0.02 | 1.29 $^{+0.02}_{-0.02}$ | 54 $^{+3}_{-3}$ | - | - | 18.7 | 1.0(417) |
| 28 | 00031921030 | 55640.5 | 2348 | - | 0.28 \pm 0.02 | 1.29 $^{+0.02}_{-0.02}$ | 57 $^{+3}_{-3}$ | - | - | 19.2 | 1.3(442) |
| 29 | 00031921031 | 55642.1 | 2137 | 1030 | 0.26 \pm 0.01 | 1.32 $^{+0.03}_{-0.03}$ | 47 $^{+4}_{-4}$ | - | - | 25.6 | 1.0(308) |
| 30 | 00031921033 | 55643.4 | 630 | 1030 | 0.11 \pm 0.06 | 1.2 $^{+0.1}_{-0.1}$ | 64 $^{+138}_{-31}$ | 2.1 $^{+0.3}_{-0.2}$ | - | 23.6 | 1.1(314) |
| 31 | 00031921034 | 55646.9 | 2166 | - | 0.12 \pm 0.02 | 1.29 $^{+0.02}_{-0.02}$ | 45 $^{+3}_{-3}$ | - | - | 15.0 | 1.2(382) |
| 32 | 00031921036 | 55650.2 | 326 | - | 0.192 \pm 0.003 | 1.28 $^{+0.04}_{-0.04}$ | 51 $^{+6}_{-6}$ | - | - | 16.9 | 0.9(196) |
| 33 | 00031921037 | 55651.5 | 2067 | 1033 | 0.22 \pm 0.02 | 1.2 $^{+0.1}_{-0.1}$ | 55 $^{+91}_{-25}$ | 2.1 $^{+0.2}_{-0.3}$ | - | 17.4 | 1.0(288) |
| 34 | 00031921038 | 55654.7 | 1173 | 1034 | 0.31 \pm 0.01 | 1.27 $^{+0.04}_{-0.10}$ | 74 $^{+163}_{-41}$ | 2.4 $^{+0.2}_{-0.3}$ | - | 29.6 | 1.2(424) |
| 35 | 00031921039 | 55655.7 | 1022 | - | 0.31 \pm 0.02 | 1.31 $^{+0.02}_{-0.02}$ | 52 $^{+4}_{-4}$ | - | - | 18.8 | 1.1(397) |
| 36 | 00031921040 | 55657.5 | 2111 | 1035 | 0.31 \pm 0.01 | 1.22 $^{+0.09}_{-0.10}$ | 57 $^{+140}_{-30}$ | 2.6 $^{+0.4}_{-0.4}$ | - | 23.4 | 0.8(216) |
| 37 | 00031921041 | 55661.9 | 974 | - | 0.32 \pm 0.02 | 1.31 $^{+0.02}_{-0.02}$ | 45 $^{+3}_{-3}$ | - | - | 16.6 | 1.1(382) |
| 38 | 00031921042 | 55667.3 | 1069 | - | 0.34 \pm 0.04 | 1.29 $^{+0.02}_{-0.02}$ | 48 $^{+3}_{-3}$ | - | - | 16.7 | 1.2(387) |
| 39 | 00031921043 | 55679.8 | 896 | - | 0.33 \pm 0.02 | 1.29 $^{+0.02}_{-0.02}$ | 48 $^{+3}_{-3}$ | - | - | 16.1 | 1.2(359) |
| 40 | 00031921044 | 55681.2 | 1035 | - | 0.26 \pm 0.04 | 1.29 $^{+0.02}_{-0.02}$ | 44 $^{+3}_{-3}$ | - | - | 15.0 | 1.1(375) |
| 41 | 00031921045 | 55683.7 | 1509 | - | 0.15 \pm 0.03 | 1.25 $^{+0.02}_{-0.02}$ | 52 $^{+3}_{-3}$ | - | - | 15.1 | 1.2(397) |

Continued on next page

Table 1: continued from previous page

| N | ID | Date | XRT EXP | INTEGRAL | rms | T _{in} | NORM | Γ | E _c | FLUX _{(2-10)keV} | χ ² _{red.} (d.o.f.) |
|----|-------------|---------|---------|----------|-----------|--|----------------------------------|-------------------------------------|----------------|---|---|
| - | - | MJD | s | REV | cnt | keV | diskbb | - | keV | (× 10 ⁻¹⁰ erg cm ⁻² s ⁻¹) | - |
| 42 | 00031921046 | 55685.3 | 1246 | - | 0.05±0.01 | 1.26 ^{+0.03} _{-0.03} | 49 ⁺⁵ ₋₅ | - | - | 13.2 | 1.1(231) |
| 43 | 00031921049 | 55691.6 | 2092 | - | 0.08±0.06 | 1.1 ^{+0.2} _{-0.1} | 37 ⁺³¹ ₋₁₆ | 2 ⁺¹ ₋₂ | - | 10.9 | 0.9(198) |
| 44 | 00031921050 | 55693.1 | 2318 | - | 0.08±0.04 | 1.0 ^{+0.1} _{-0.1} | 62 ⁺⁹ ₋₁₅ | 1 ⁺¹ ₋₂ | - | 9.7 | 1.0(311) |
| 45 | 00031921051 | 55695.0 | 1139 | - | 0.08±0.03 | 1.2 ^{+0.2} _{-0.2} | 15 ⁺⁹ ₋₉ | 2.4 ^{+0.3} _{-0.3} | - | 9.1 | 1.0(303) |
| 46 | 00031921052 | 55697.8 | 1160 | - | 0.07±0.04 | 1.1 ^{+0.2} _{-0.1} | 26 ⁺²³ ₋₁₂ | 2.4 ^{+0.3} _{-0.4} | - | 8.7 | 1.2(298) |
| 47 | 00031921053 | 55701.8 | 1188 | - | 0.10±0.02 | 1.1 ^{+0.2} _{-0.1} | 20 ⁺¹⁹ ₋₁₀ | 2.4 ^{+0.3} _{-0.4} | - | 8.6 | 1.1(300) |
| 48 | 00031921054 | 55703.7 | 2291 | - | 0.08±0.02 | 1.0 ^{+0.2} _{-0.1} | 30 ⁺²³ ₋₁₉ | - | - | 9.6 | 1.0(299) |
| 49 | 00031921055 | 55705.6 | 2374 | - | 0.15±0.03 | 1.23 ^{+0.02} _{-0.02} | 49 ⁺⁴ ₋₃ | - | - | 13.6 | 1.1(375) |
| 50 | 00031921056 | 55707.4 | 1789 | - | 0.26±0.02 | 1.24 ^{+0.02} _{-0.02} | 50 ⁺³ ₋₃ | - | - | 14.4 | 1.1(386) |
| 51 | 00035096002 | 55715.7 | 894 | - | 0.18±0.04 | 1.27 ^{+0.02} _{-0.02} | 47 ⁺⁴ ₋₄ | - | - | 14.7 | 1.3(345) |
| 52 | 00035096003 | 55717.7 | 1006 | - | 0.12±0.02 | 1.20 ^{+0.02} _{-0.02} | 46 ⁺⁴ ₋₃ | - | - | 11.3 | 1.3(334) |
| 53 | 00035096004 | 55719.5 | 907 | - | 0.13±0.05 | 1.23 ^{+0.02} _{-0.02} | 45 ⁺⁴ ₋₃ | - | - | 12.3 | 1.1(323) |
| 54 | 00035096005 | 55721.3 | 1070 | - | 0.17±0.02 | 1.24 ^{+0.02} _{-0.02} | 49 ⁺⁴ ₋₃₇ | - | - | 13.9 | 1.1(369) |
| 55 | 00035096009 | 55725.6 | 1151 | - | 0.06±0.03 | 1.20 ^{+0.02} _{-0.02} | 46 ⁺⁴ ₋₃ | - | - | 9.0 | 1.3(334) |
| 56 | 00035096010 | 55729.4 | 1006 | - | 0.07±0.04 | 1.3 ^{+0.3} _{-0.3} | 8 ⁺¹³ ₋₃ | 2.5 ^{+0.9} _{-0.4} | - | 7.8 | 1.0(247) |
| 57 | 00035096012 | 55731.0 | 437 | - | 0.07±0.05 | 1.09 ^{+0.04} _{-0.02} | 18 ⁺⁴² ₋₁₂ | 2 ⁺¹ ₋₁ | - | 8.1 | 0.8(132) |
| 58 | 00035096014 | 55733.2 | 928 | - | 0.11±0.05 | 1.0 ^{+0.1} _{-0.1} | 43 ⁺²⁶ ₋₁₉ | 2 ⁺¹ ₋₅ | - | 7.8 | 1.0(238) |
| 59 | 00035096015 | 55735.3 | 1102 | - | 0.10±0.03 | 1.1 ^{+0.1} _{-0.1} | 49 ⁺³⁰ ₋₁₃ | 3 ⁺¹ ₋₁ | - | 12.5 | 1.1(283) |
| 60 | 00035096016 | 55737.5 | 140 | - | 0.16±0.04 | 1.2 ^{+0.1} _{-0.1} | 51 ⁺¹⁹ ₋₁₄ | - | - | 11.8 | 1.0(46) |
| 61 | 00035096017 | 55739.4 | 992 | - | 0.32±0.05 | 1.2 ^{+0.03} _{-0.03} | 33 ⁺⁴ ₋₃ | - | - | 8.1 | 0.9(224) |
| 62 | 00035096018 | 55741.6 | 1123 | - | 0.39±0.03 | 1.47 ^{+0.03} _{-0.03} | 25 ⁺² ₋₂ | - | - | 15.2 | 1.3(375) |
| 63 | 00035096019 | 55744.0 | 984 | - | 0.37±0.02 | 1.58 ^{+0.04} _{-0.04} | 19 ⁺² ₋₂ | - | - | 17.2 | 1.1(350) |
| 64 | 00035096020 | 55759.3 | 850 | - | 0.36±0.05 | 1.67 ^{+0.06} _{-0.05} | 18 ⁺² ₋₂ | - | - | 19.6 | 1.1(210) |
| 65 | 00035096021 | 55761.5 | 727 | - | 0.42±0.03 | 1.50 ^{+0.04} _{-0.03} | 24 ⁺² ₋₂ | - | - | 16.1 | 1.2(311) |
| 66 | 00035096022 | 55765.3 | 956 | - | 0.41±0.04 | 1.35 ^{+0.03} _{-0.03} | 36 ⁺³ ₋₃ | - | - | 15.0 | 1.0(363) |
| 67 | 00035096023 | 55767.3 | 940 | - | 0.38±0.04 | 1.32 ^{+0.02} _{-0.02} | 37 ⁺³ ₋₃ | - | - | 14.0 | 1.1(346) |
| 68 | 00035096027 | 55775.3 | 863 | - | 0.39±0.03 | 1.34 ^{+0.03} _{-0.02} | 38 ⁺³ ₋₃ | - | - | 15.3 | 1.1(342) |
| 69 | 00035096028 | 55777.9 | 354 | - | 0.22±0.01 | 1.27 ^{+0.04} _{-0.04} | 47 ⁺⁷ ₋₆ | - | - | 14.9 | 1.2(165) |
| 70 | 00035096029 | 55779.4 | 511 | - | 0.23±0.06 | 1.24 ^{+0.04} _{-0.03} | 50 ⁺⁶ ₋₅ | - | - | 14.3 | 1.0(237) |
| 71 | 00035096030 | 55783.8 | 547 | - | 0.34±0.03 | 1.30 ^{+0.04} _{-0.04} | 82 ⁺¹¹ ₋₁₀ | - | - | 29.0 | 1.1(198) |
| - | - | 55785.0 | - | 1078 | - | 1.3 ^{+0.1} _{-0.1} | 58 ⁺³² ₋₂₀ | 2.3 ^{+0.2} _{-0.2} | - | 24.7 | 1.1(26) |
| 72 | 00035096032 | 55787.7 | 974 | - | 0.37±0.04 | 1.28 ^{+0.02} _{-0.02} | 58 ⁺⁵ ₋₅ | - | - | 19.2 | 1.1(352) |

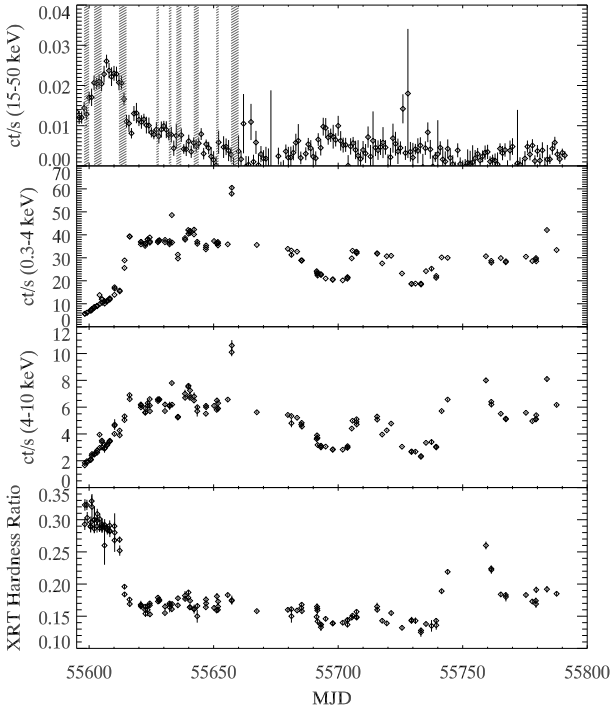


Figure 1. Top panel: *Swift*/BAT (15–50 keV) count rate (bin time= 1 day). The shadowed parts represent the *INTEGRAL* observation periods. Second panel: XRT (0.3–4 keV) count rate (bin time =4000s). Third panel: XRT (4–10 keV) count rate (bin time =4000s). Bottom panel: XRT Hardness Ratio (defined as the ratio between the 4–10 keV to the 0.3–4 keV count rate).

3 RESULTS

The 2011 outburst of IGR J17091–3624 can be divided in two main phases: during the first one, the source underwent the typical sequence of events of a transient BH in outburst (described in Section 3.1); during the second part, it exhibited “heartbeat” variability previously observed only in GRS 1915+105 (Sections 3.2 and 3.3). Finally, a detailed study on the presence of a Compton reflection component and iron line upper limit are given in Section 3.4.

3.1 The initial phases of the outburst

The outburst of IGR J17091–3624 started on MJD~55598 (Figure 1) and in about 12 days the X-ray flux of the source (2–10 keV) increased of about 70%. During this starting phase, the *Swift* and *INTEGRAL* simultaneous data, when available, could be well fit by an absorbed cutoff power-law model. The source showed a typical hard state spectrum and the photon index and high-energy cutoff remained consistent within the errors ($\Gamma \sim 1.5$, $E_c \sim 100$ keV, see Table 1 for details). The equivalent hydrogen column density value was consistent with the one reported by Krimm & Kennea (2011), $N_H = (1.1 \pm 0.3) \times 10^{22} \text{ cm}^{-2}$.

Figure 2 shows the combined XRT-ISGRI unfolded LHS spectrum along with the residuals expressed in terms of sigmas (MJD=55603.2, observation n°6 in Table 1).

On MJD~55610.2, the source displayed evidence for a beginning of a spectral transition to the softer state. The flux continued to increase more rapidly: $\sim 100\%$ from the observation n°12 until the observation n°15 (about 6 days). But, this time, a significant softening of the hard X-ray spectrum (see i. e. bottom panel of Figure 1) was observed, together with a drop in the hard X-ray flux.

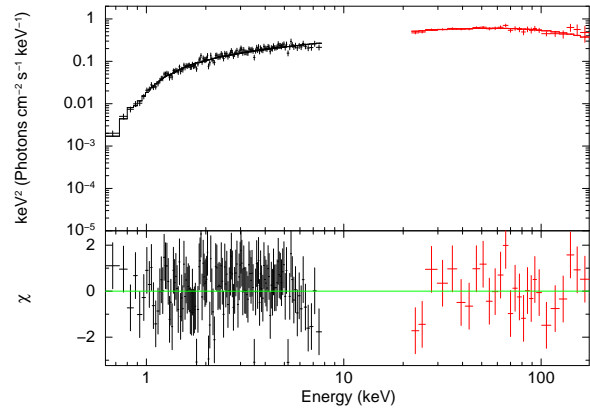


Figure 2. *Swift*/XRT and *INTEGRAL*/IBIS joint unfolded spectrum at the beginning of the outburst. The source presents a typical LHS spectrum (observation n°3 in Table 1).

During the transition the spectra became steeper and in about two days the fit required a multicolor disc blackbody component (modeled with `diskbb` in XSPEC, Mitsuda et al. 1984, hereafter MDBB). Figure 3 shows two spectra extracted at the intermediate hardness values (HR~0.2, observation n°13 and n°14). An acceptable fit to these spectra could be obtained by using an absorbed cutoff power law model). Adding the MDBB component, the F-test probability of a chance improvement is 7% and 0.4%, for the observations n°13 and n°14, respectively. Thus it is reasonable to add a MDBB component only to the second spectrum.

The obtained spectral parameters of the spectrum n°14 are compatible with the intermediate spectral states of a BHC (see e. g. Fender et al. (2004) and Remillard & McClintock (2006) and references therein). During this transition from the hard to the soft state, the inner temperature of the MDBB component (kT_{in}) increased from 0.3 keV (observation n°14) to ~ 1 keV (observations n°15÷16), while its normalization decreased significantly³.

At the end of the transition to the soft state (observation n°16), the disc temperature reached a value of about 1 keV, while the power law photon index reached ~ 2.1 , with no cutoff detectable up to about 200 keV (see Table 1 for details). The fractional *rms* amplitude of the X-ray emission from IGR J17091–3624 as measured by XRT data decreased from previous values (25÷30%) up to about 4÷5% (see Figure 5). Thus, as also reported by Del Santo et al. (2011), the source is probably in the HSS. In the following 65 days (until observation n°42) the spectral characteristics of the source showed no significant variability. Figure 4 shows the unfolded spectrum of IGR J17091–3624 after the transition (observation n°33). The fit to these data was obtained with an absorbed MDBB plus a simple power law component. No Compton-reflection from the disc surface and no iron line models were required by the data even though these components are usually expected to be very strong in the canonical soft state of BH binaries (Gierlinsky et al. 1999).

On MJD=55655.8 (observation n°34) a short flare, reaching a peak flux of $3 \times 10^{-9} \text{ erg cm}^{-2} \text{ s}^{-1}$ (2–10 keV) was detected.

³ In the MDBB model (Mitsuda et al. 1984) the square root of the normalization constant is proportional to the apparent inner radius of the truncated disc. However, when the high energy behaviour of the spectrum is modeled with a power law component, the evolution of the disc internal radius can be significantly underestimated (see e. g. Done et al. 2007, p. 28–29).

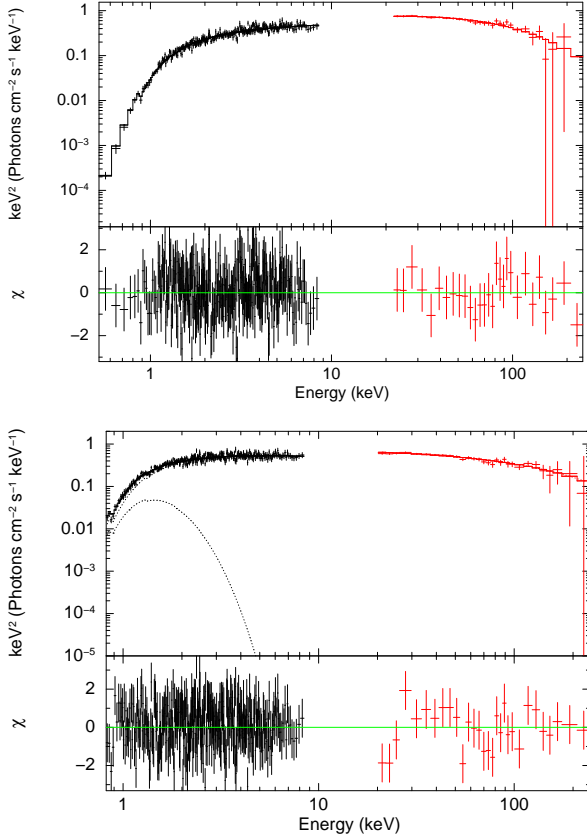


Figure 3. Two *Swift*/XRT and *INTEGRAL*/IBIS joint intermediate spectra during the transition from the Low Hard State (LHS) to the High Soft State (HSS). The two spectra have been collected from data separated by 2 days. Top spectrum: observation n°13 in Table 1. Bottom spectrum: observation n°14 in Table 1.

No significant changes in the spectral properties of the source were detected during this event.

3.2 The appearance of the “heartbeat”

Figure 5 shows the fractional *rms* amplitude as a function of the hardness ratio, hereafter HR⁴. As mentioned above, during the transition from the hard to the soft state, the fractional *rms* and the HR decreased as expected by a typical transient BH entering the HSS (Fender et al. 2004).

However, from observation n° 26 the fractional *rms* amplitude moved away from the expected values and started to increase and decrease rapidly with a chaotic behaviour (see e. g. Figure 5). The rapid increases correspond to the observations in which the quasi-periodic flare-like events are detected in the light curves (the “heartbeat” in analogy with GRS 1915+105, see also Section 1). As an example, Figure 6 shows a zoom of the light curve of one of the XRT observations in which the “heartbeat” is detected. The “heartbeat” oscillations vary in intensity and in hardness; in some observations they are not detected at all (in these cases lower values of the fractional *rms* amplitude are measured). No significant variations can be observed in the spectra of each XRT observation

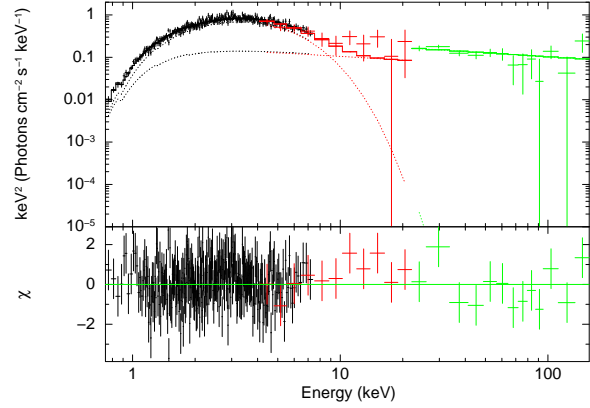


Figure 4. *Swift*/XRT *INTEGRAL*/JEM-X2 and *INTEGRAL*/IBIS unfolded spectra of the IGR J17091–3624 soft state (see Section 4). The fit is an absorbed MBB plus a power law. No reflection component is needed in the fit (the spectral parameters values are reported in Table 1, observation n°33).

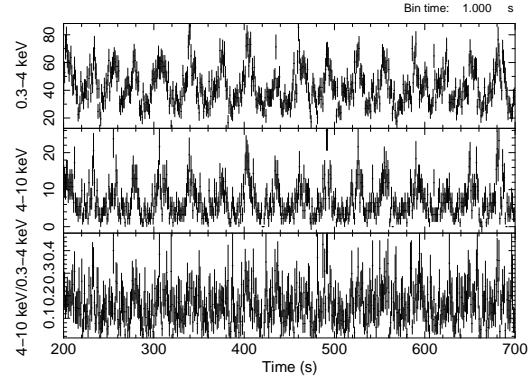


Figure 6. Zoom of the XRT count rate of the observation n°28 in Table 1. The time bin is 1 s and the start time is MJD=55640.5.

with or without the presence of the “heartbeat”. We also observed that the flare-like events lose coherence and change their period with time. Figure 7 shows the evolution of the “heartbeat” period as a function of time. This behaviour is consistent with what observed with *RXTE* (Altamirano et al. 2011a,d). The two panels of Figure 8 show the “heartbeat” period as a function of hardness and XRT count rate, respectively. No evident correlation between the periods of the flare-like events with the count rate or the HR has been found. The only peculiarity is the presence of a sort of “forbidden zone” in the possible period values (from ~40 s to ~65 s, Figures 7, 8). For a detailed discussion of the different “heartbeat” states of IGR J17091–3624 see Altamirano et al. (2011d).

No significant detection of the “heartbeat” was found in the IBIS light curve because of the faintness of the source in the hard X-ray domain (20–200 keV) and the relatively poor statistics.

After MJD~55690 (observations n° 43–44), the “heartbeat” was no longer detected and at the same time the flux in the 15–50 keV energy band started to increase again (see the BAT light curve in Figure 1). The spectral analysis of the observations collected during this period showed that the inner temperature of the MBB component decreased down to ~1 keV and a power-law component was also required in order to have an acceptable fit of the XRT spectra. In the previous observations, a power law component additional to MBB was required only when XRT and IBIS

⁴ We defined as the hardness ratio the ratio of the counts in the 4–10 keV energy band to the counts in the 0.3–4 keV energy band in each XRT observation.

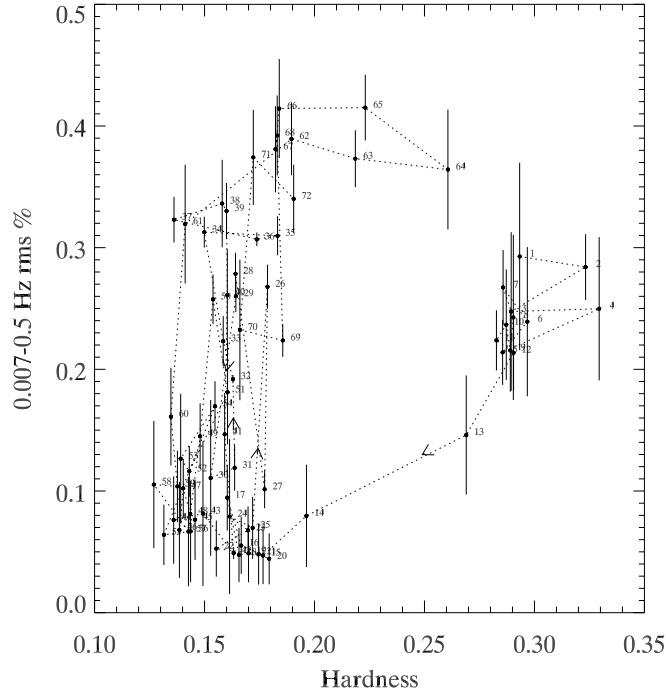


Figure 5. Hardness-rms diagram of each XRT pointing of the IGR J17091–3624 outburst. For the observations with more than one segment only the first one has been considered. For the usage of *rms* as a tracer of the different accretion regimes see e. g. Munoz-Diaz et al. (2011) and Capitanio et al. (2009b). In order to get a more readable Figure, we did not show the hardness error bars that are, instead, reported in Figure 11.

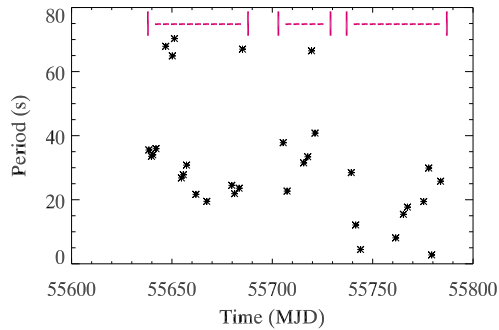


Figure 7. “heartbeat” period versus time. The dashed segments represent the three different groups of observations discussed in the text.

data were fitted simultaneously. Between observations n°37-41 the *INTEGRAL* data were unavailable, and thus we could not constrain the properties of the source emission in the hard X-ray domain.

On MJD=55705.6 (observation n°49), the 15–50 keV light curve started to decrease again. Correspondingly, the soft XRT light curve increase significantly (see Figure 1) and the XRT spectra reached again approximately the same shape observed during the previously detected soft state. On the same date, MJD=55705.6, a second group of recurrent flare-like events appeared again in the light curves. At this time the flux variation of the flare events was less pronounced and less coherent, while the periods scanned approximately the same range than in the previous group of events (see Figure 7).

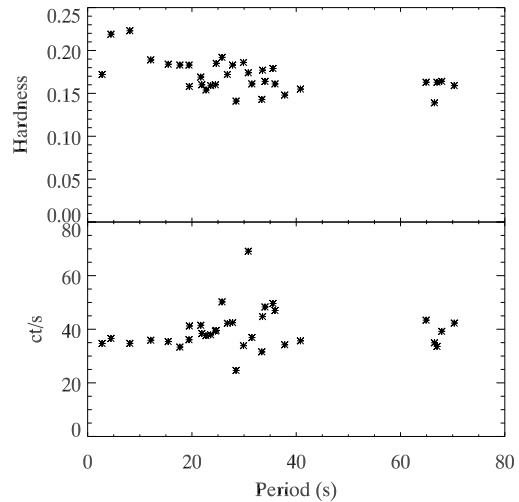


Figure 8. Top panel: hardness versus “heartbeat” period. Bottom panel: XRT count rate versus “heartbeat” period.

As Figure 1 shows, from MJD~55730 until 55770 there was an increase of the XRT flux together with a sharp hardening. The consequence of the hardening in the XRT spectra are an increase of the inner disc temperature and a decrease of the normalization constant of the MBB model, *NORM*, that reached values of about ~18 (see Table 1). In particular *NORM* is proportional to the square of the apparent inner disc radius and to $\cos i$, where i is the angle

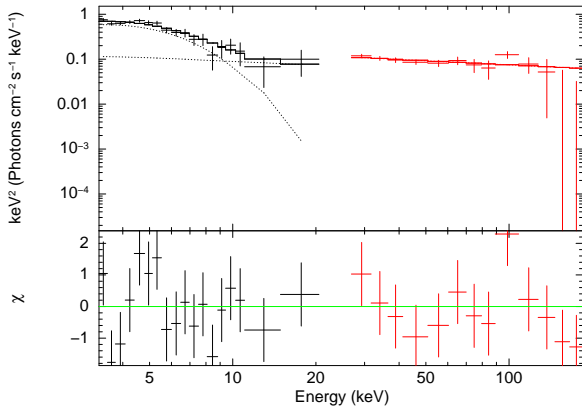


Figure 10. *INTEGRAL*/JEM-X2 and *INTEGRAL*/IBIS averaged spectrum of IGR J17091–3624 in the soft state during revolution 1078 (MJD=55785.0). The fit is an absorbed MDBB plus a power law. The spectral parameters are reported in Table 1.

between the disc and the observer (Mitsuda et al. 1984).⁵ Thus in order to obtain an inner radius with a plausible length, $\cos i$ should be very small. Simultaneously to the spectral hardening, the XRT light curves and the corresponding power spectra clearly showed that a third group of recurrent flare-like events started with a remarkably decreased period (see Figure 7).

As an example, the four panels of Figure 9 show the XRT power spectra evolution, from MJD=55737.5 to MJD=55759.3 (observations n°60–64). This time interval corresponds to the reappearance of the flare-like events: at MJD=55737.3 (observation n°60) there were no flare-like events and the power spectrum presented a power law like behaviour (panel *a*). On MJD=55741.6 the flare-like events started again and a prominent and broad feature appeared in the power spectrum shape (panels *b* and *c*). The frequency of this feature changed with time from ~ 0.72 Hz to ~ 0.22 Hz (panels *d* and *e*).

The “heartbeat” is always detected during the final part of the *Swift* campaign with periods that span from about 3 s until 30 s. The energy spectra of each single XRT observation were fitted with the same model than before (absorbed multicolor disc black body plus a power law component). However, after the observation n°65, the inner temperature of the MDBB component decreased from ~ 1.5 keV to ~ 1.3 keV (see Table 1 for details). The *INTEGRAL* observations, performed during revolution 1078 (MJD=55785.0), showed that the fit of the hard part of the spectrum is consistent with a simple power law component with a photon index of $\Gamma=2.3\pm 0.2$ (see Figure 10).

We also note that during the periods in which IGR J17091–3624 displayed evidence for the “heartbeat” phenomena, its spectral evolution remained trapped in the top left corner of the hardness-intensity diagram (hereafter HID; see Figure 11) and outlined no more the canonical path through the different spectral states expected from a BHC in outburst (the so called q-track).

3.3 Spectra from the “heartbeat”

In order to investigate the origin of the changes in the hardness ratio during the “heartbeat”, we extracted XRT spectra in the time intervals corresponding to the highest (>60 ct/s) and lowest (<30 ct/s) count rates of the source spectra during the flaring activity. For these data, we performed a rate resolved analysis adding-up time intervals corresponding to the peaks and to the minima of the flare in each observation (note, however, that the hardening of the different peaks was not constant; see for example the HR behaviour in Figure 6). Because of the periodicity of the light curve, the rate resolved analysis overlaps with the phase resolved analysis.

A fit to the spectra was obtained by using an absorbed MDBB component. The spectral parameters at highest count rates indicated a higher inner disc temperature and a hint for a smaller inner disc radius (see Table 2 for details) than what measured at lower count rates. This behaviour is more evident in some observations of the first group of data showing recurrent flare like events (between MJD ~ 55630 and MJD ~ 55690), where the flux variation during the flares was more pronounced. In fact, unfortunately, due to the low data statistics, only in a few observations was it possible to constrain the MDBB normalization constant with enough confidence.

In the second group (from MJD ~ 55700 to MJD ~ 55730) the changes in the HR with the source count rates and the coherence of the “heartbeat” oscillation are less evident. We report in Table 2 the spectral parameters of three representative XRT observations selected at different time periods. The N_H is fixed to be the same for the different phases of the same observations.

The unfolded phase-resolved spectra obtained for the XRT observation n°30 (MJD=55640.5) are shown in Figure 12. We found evidence that the flares are due to an oscillation of the inner disc boundary (Table 2): at the peak of the flare the MDBB temperature (radius) is higher (smaller) with the disc approaching the BH event horizon. The opposite behaviour is observed during the minima of the flare. This is similar to what has been observed in the case of GRS 1915+105 (Neilsen et al. 2011). The lower X-ray flux of IGR J17091–3624 with respect to GRS 1915+105, however, does not allow us to study the “heartbeat” in the same details. Theoretical studies suggest that this phenomenon is due to the Lightman-Eardley instability, a limit cycle in the inner accretion disc dominated by the radiation-pressure (Lightman & Eardley 1974; Nayakshin & Rappaport 2000; Szuszkiewicz & Miller 1998). According to this interpretation, the inner part of the disc empties and refills with a timescales of seconds (Belloni et al. 1997).

3.4 Reflection component

In order to investigate the presence of Compton-reflection component and the iron line in the spectra of IGR J17091–3624, we used the XRT, JEM-X and IBIS joint spectra showed in Figure 10. In this case the spectral parameters revealed that IGR J17091–3624 is in the soft state (observation n°33) when the highest contribution from the reflection component is expected (see e. g. Ross & Fabian 2007, and reference therein). The model used to fit the data is an absorbed MDBB plus an exponentially cut-off power-law spectrum reflected by neutral material (*pexrav* in XSPEC; Magdziarz & Zdziarski 1995).

Considering the distance of the source estimated by Pahari et al. (2011b) and Rodriguez et al. (2011b), we took into account also the hypothesis that the source could belong to the Galactic halo and thus have a different metallicity with respect to the sources in the Galactic bulge, where normally LMXBs are con-

⁵ The connection between the apparent inner disc radius and the inner radius itself is reported by Kubota et al. (1998).

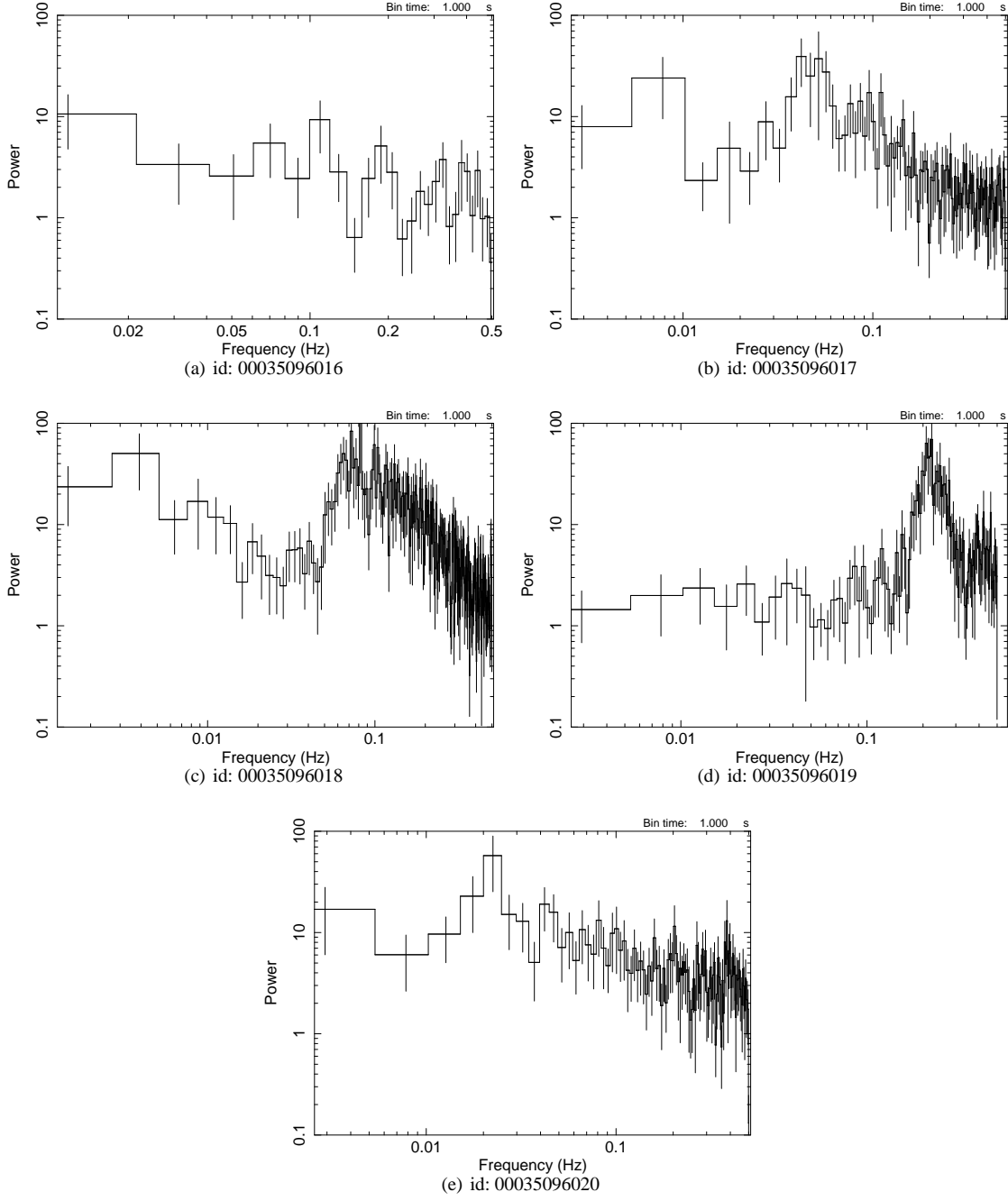


Figure 9. XRT power spectra evolution of five observations (binned at 1s), from MJD=55737.5 to MJD=55759.3 (observation n°60÷64), that correspond to the reappearance of the flare-like events of the last part of the XRT campaign of IGR J17091–3624.

centrated (Grimm et al. 2002). No significant changes in the spectral fits were observed by leaving the metallicity of the reflecting medium free to vary. We thus assumed two different values of the metallicity, i.e. the solar one (the source belongs to Galactic bulge, $Z/Z_{\odot} = 1$) and $Z/Z_{\odot} = 0.13$ as reported by Frontera et al. (2001) for XTE J1118+480 which is a BH binary that lies at very high Galactic Latitudes. In both cases the estimated upper limit on the reflection component was of $R=0.1$, and the F-test probability indicated that there is not a clear evidence of a significant improvement in the χ^2 by adding this component (the F-test probability in the two cases was of 7% and 2%, corresponding to a detection significance of $<2.0\sigma$ and $<2.5\sigma$, respectively).

We also estimated an upper limit on the normalization of the iron line fixing the centroid of the line at 6.7 keV. We assumed a broad line with $\sigma=0.7$ keV as in the case of GRS 1915+105 (see e. g. Martocchia et al. 2002, and references therein). The obtained upper limit on the equivalent width is $EQ < 0.9$ keV.

4 DISCUSSION

All the outbursts of IGR J17091–3624 observed before 2011 were fainter and poorly observed with respect to the last one. However the source, in the limit of the instruments capability, displayed

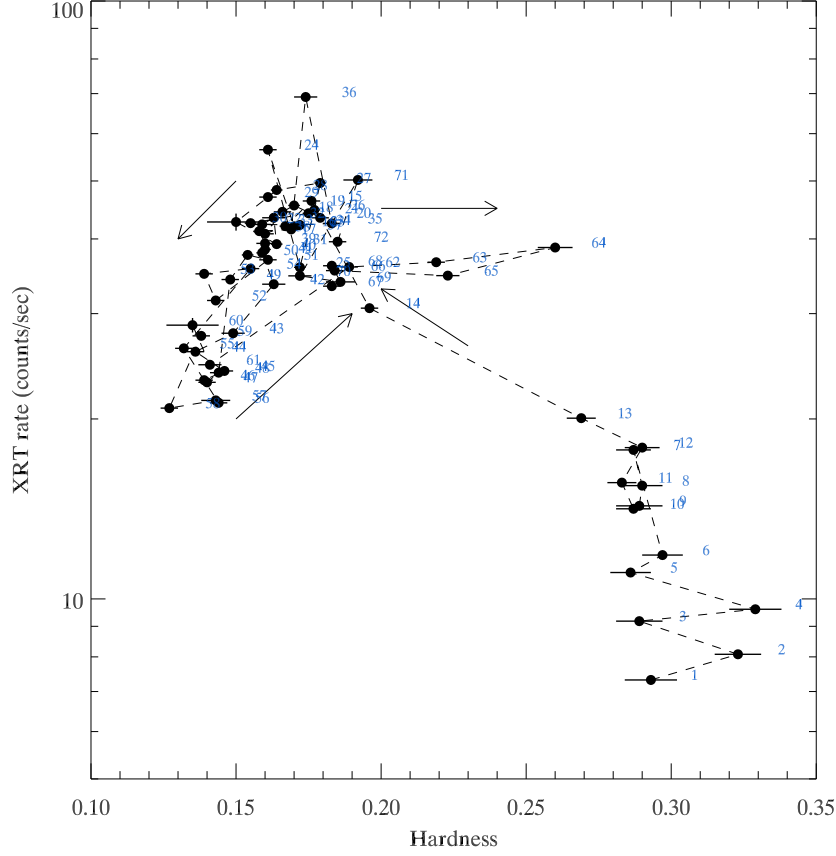


Figure 11. Hardness-intensity diagram (HID) of all the XRT 2011 outburst observations of IGR J17091–3624. For the observations with more than one segment only the first one has been considered.

Table 2. Spectral parameters of the different phases of three XRT observations: *N* is the number of the XRT observation as in Table 1; *H*: maxima count rate intervals (> 60 ct/s); *L*: minima count rate intervals (< 30 ct/s).

| <i>N</i> | ID | Phase | T_{in} keV | NORM <i>diskbb</i> | $F_{(0.1-10keV)}$ ($\times 10^{-9} \text{ erg cm}^{-2} \text{ s}^{-1}$) | $\chi^2_{red.}$ | d.o.f. |
|----------|-------------|----------|------------------------|-----------------------|--|-----------------|--------|
| 26 | 00031921028 | <i>H</i> | $1.4^{+0.1}_{-0.1}$ | 69^{+12}_{-10} | 6 | 1.04 | 67 |
| 26 | 00031921028 | <i>L</i> | $1.1^{+0.1}_{-0.1}$ | 81^{+27}_{-21} | 2 | 1.17 | 24 |
| 28 | 00031921030 | <i>H</i> | $1.49^{+0.03}_{-0.03}$ | 52^{+4}_{-4} | 6 | 0.99 | 212 |
| 28 | 00031921030 | <i>L</i> | $1.10^{+0.03}_{-0.03}$ | 63^{+8}_{-7} | 2 | 1.02 | 83 |
| 38 | 00031921042 | <i>H</i> | $1.6^{+0.1}_{-0.1}$ | 37^{+5}_{-4} | 5 | 0.88 | 112 |
| 38 | 00031921042 | <i>L</i> | $1.00^{+0.02}_{-0.02}$ | 83^{+8}_{-7} | 2 | 0.98 | 128 |
| 51 | 00035096002 | <i>H</i> | $1.4^{+0.1}_{-0.1}$ | 52^{+12}_{-10} | 4 | 0.85 | 42 |
| 51 | 00035096002 | <i>L</i> | $1.18^{+0.03}_{-0.03}$ | 46^{+5}_{-4} | 2 | 1.00 | 126 |
| 54 | 00035096005 | <i>H</i> | $1.5^{+0.1}_{-0.1}$ | 38^{+8}_{-7} | 4 | 1.3 | 64 |
| 54 | 00035096005 | <i>L</i> | $1.23^{+0.03}_{-0.03}$ | 40^{+3}_{-3} | 2 | 1.10 | 185 |

the typical spectral and temporal evolution (Capitanio et al. 2005, 2009a) expected from a canonical BHC (for details on the transient BHC outburst evolution see e.g., Fender et al. 2004). The “heartbeat” phenomenon appeared only during the last 2011 outburst. Indeed, using all the available archival XRT observations in the di-

rection of IGR J17091–3624, we verified that no “heartbeat” was visible during the previous outbursts of the source.

We summarize here the initial evolution phases of the outburst occurred on 2011. The source underwent to a transition from the LHS to the HSS moving from the bottom right corner of the HID to the top left corner (Figure 11, observations n° 1÷15):

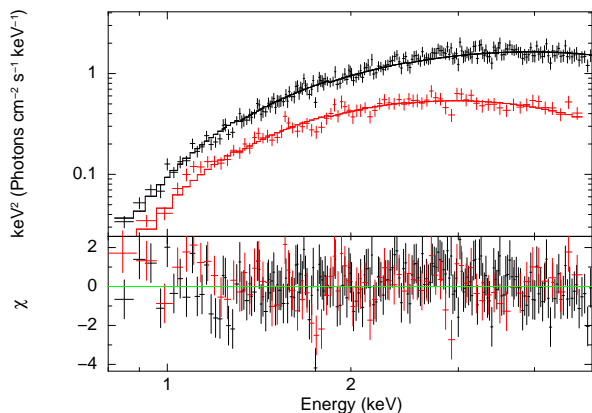


Figure 12. Count rate resolved spectra of the observation 00031921030. The upper spectrum was extracted during time intervals corresponding to the peaks of the flare-like events observed in this observation. The lower spectrum corresponds to the time intervals of the flares where the source count rate was a minimum. The two spectra were fit together with unabsorbed MDBB model (we constrained the N_H to be the same for the two spectra and we let the other parameters to vary independently).

- during this transition, the source reached the intermediate states and the radio flare reported by Rodriguez et al. (2011b) should be the signature of the transition from the HIMS to the SIMS (Fender et al. 2004);
- the *rms* amplitude starting from values of about $\sim 30\%$ in the LHS, decreased significantly reaching values that span from 6% to 2% (see Figure 5 and column n°6 in Table 1);
- the spectrum became softer with the presence of a prominent disc blackbody component (starting from observation n°15) with the high energy cutoff no longer detectable up to 200 keV.

The source remained in the HSS for about 10 days (from MJD=55623.5 till MJD=55633.3). Starting from MJD=55635 the source followed no more the standard evolution of a transient BHC in outburst: the properties of the X-ray spectra in each observation showed no significant variability, while the source displayed a sudden atypical timing variability in the form of flare-like events occurring at a 33 s period (“heartbeat”). The X-ray emission at the peak of these flares is typically harder than the average source emission (see the third panel of Figure 6).

Starting from MJD=55692 we measured a progressive decrease of the MDBB inner temperature with a corresponding hardening of the source emission. At this time the flare-like events were no longer visible in the light curve. The hardening continued uninterrupted for about two days, then the inner temperature of the disc started to increase again, leading to a clear increase in the soft X-ray flux and a decrease of the hard X-ray emission. At this epoch, the “heartbeat” became again visible.

The last part of the data analysed presented a short period oscillations (between 3 s and 30 s) and also a particularly hot inner disc temperature with a very small MDBB normalization constant that corresponds to a small apparent inner radius. Between MJD=55740 and MJD=55760, the 4–10 keV XRT flux increased significantly (a factor of 60%). The peak in the 4–10 keV flux (see Figure 1) corresponds to a peak in the inner disc temperature ($T_{in} \sim 1.7$ keV on MJD=55759.3).

The period of the “heartbeat” changed with time (Figure 7) and it seems to have a decreasing trend.

4.1 Comparison with the BH binary GRS 1915+105

As reported by Altamirano et al. (2011d) and by Pahari et al. (2011b) the behaviour of the source resembles what observed from GRS 1915+105 in the various flaring states. Thus the principal common characteristic between these two sources is just the presence of pseudo periodic flare-like events in the light curve i. e. the so called “heartbeat”. The HR (bottom panel of Figure 6) of IGR J17091–3624 is similar to the GRS 1915+105 one, in the sense that in both sources the modulation of the light curve is projected also in the HR (Nielsen et al. 2011). However, in the GRS 1915+105 case the hardness variation seems more pronounced (see for example Naik et al. 2002). Our phase resolved energy spectra of the XRT data revealed that the hardening of the source X-ray emission at the peak and at the lower part of each flare is similar to what measured in the case of GRS 1915+105 (see e. g. Mineo et al. 2010; Belloni et al. 1997) and thus it is probably due to the same physical phenomenon (Lightman & Eardley 1974).

The period of the “heartbeat” seems also to vary with time in the same range of values for the two sources, even though in GRS 1915+105 the period amplitude gets larger for long time scales. This does not seem to be the case for IGR J17091–3624. Indeed, as showed in Figure 7, the period variation with time seems to decrease and, moreover, in the third group of observations (from MJD=55750 until the end) it reaches values of the order of few seconds ($\sim 3\div 5$ s). These values were not observed in GRS 1915+105 (Nielsen et al. 2011).

Similarly to GRS 1915+105, we measured also for IGR J17091–3624 particularly hot inner disc temperatures (in the case of GRS 1915+105 the temperature can reach even higher values; see e.g., Belloni et al. 1997; Munro et al. 1999; Fender & Belloni 2004)⁶. This property, together with a small inner radius of the disc blackbody spectrum in X-ray binaries, has been directly associated with high values of the BH spin (Zhang et al. 1997; Devis et al. 2006).

Besides all these similarities between GRS 1915+105 and IGR J17091–3624, a particularly striking difference is the X-ray flux intensity during the outbursts. This fact cannot be easily explained because, unlike GRS 1915+105, for IGR J17091–3624 we do not have an estimation of the distance, the inclination angle, BH mass and spin, and the properties of the companion star. Some results on optical and NIR counter-part of IGR J17091–3624 have been reported by Torres et al. (2011).

Chaty et al. (2008), on the basis of optical and NIR photometric and spectroscopic studies of two possible counter-parts of the source, suggested that the source should belong to the Galactic bulge. However, Rodriguez et al. (2011b) recently estimated a lower limit of the source distance from its hard to soft transition luminosity concluding that, if the transition occurred at luminosity that spans from 4% to 10% of the Eddington luminosity (assuming a BH mass of $10 M_\odot$), IGR J17091–3624 is farther from the Galactic bulge, at a distance that spans from about 11 kpc up to

⁶ The inner disc radius values reported for GRS 1915+105 by Munro et al. (1999) and related to inner temperatures greater than 1.6 keV, are too small to be associated with the ISCO for any reasonable black hole mass. Even if the hard part of the spectrum, modeled using a power law, could underestimate the inner disc radius (Done et al. 2007), it is not possible to exclude that, in these cases, the accretion geometry could be different from the one predicted by MDBB. However this should not be the case for IGR J17091–3624. In fact, the spectral parameters reported in our analysis are not as extreme as the ones reported by Munro et al. (1999) for GRS 1915+105.

17 kpc. Moreover Pahari et al. (2011b), using a different method, based on QPO, estimated an even larger distance of 20 kpc and a mass range that spans from $8M_{\odot}$ to $11.4M_{\odot}$.

Assuming a distance range of 11-17 kpc, the bolometric luminosities of IGR J17091–3624 estimated from the observation displaying “heartbeat” with the highest flux would be $(3-7) \times 10^{37}$ erg s $^{-1}$ which translates in to $L \sim (3-6)\% L_{Edd}$. However, considering the distance and the BH mass range supposed by Pahari et al. (2011b) these luminosities result in 1% and 8% L_{Edd} .

Since the flare-like events should be at Eddington limit regime (see e.g. Nayakshin & Rappaport 2000; Neilsen et al. 2011, and reference therein), if we consider the values reported above, we conclude that the faintness of IGR J17091–3624 should not be only due to the source distance. For this reason Altamirano et al. (2011d) supposed that the distance of the source could be even larger than 20 kpc, otherwise the BH mass should be extremely small (less than $3M_{\odot}$).

Other peculiar differences of IGR J17091–3624 with respect to GRS 1915+105 are the lack of detection of the Compton-reflection component and the extremely low apparent inner disc radius (see Section 3.2).

Taking these results as a whole, we speculate that IGR J17091–3624 could be a highly inclined system and we suggest that the lower luminosity of IGR J17091–3624 could be also ascribed to the spectral deformation effects due to the high inclination angle as reported by Cunningham (1998). Indeed, when a Kerr BH is seen at a high inclination angle ($\cos i < 0.25$, $i \sim 75$ degrees), the source appears significantly fainter (up to a factor that depends on the BH spin and mass but can reach about an order of magnitude less) with respect to system observed face-on.

At odds with this hypothesis is the lack of detection of eclipses. Although we do not have any information about the system, such as the orbital period or the companion star mass, we can speculate that the lack of eclipses could be related to a small ratio between the companion star and BH mass. Using the Eggleton approximation (Eggleton 1983), we calculated the relation between the mass ratio, q (M_{star}/M_{BH}) and the Roche lobe radius. Then, the minimum inclination angle, i , for which the Roche lobe does not cover the central engine along the observer line of sight, is extracted from simple geometrical considerations giving:

$$R_L/a < \cos i \quad (1)$$

where R_L is the Roche Lobe radius calculated with the Eggleton approximation; a is the distance between the BH and the companion star; i is the inclination angle of the system. Plotting R_L/a versus q (Eggleton 1983) and considering the equation 1, we found that for $q < 0.2$, the Roche lobe does not cover the central engine for inclination angles smaller than 75 degrees (Cunningham 1998).

Moreover, the lack of information on the orbital period of the system hampers the search for the eventual presence of partial eclipses via the usual light curve folding techniques that increase the signal to noise ratio.

5 CONCLUSIONS

The outcome of the observational campaign presented here suggests that IGR J17091–3624 can be no longer considered as typical transient Black Hole (Fender et al. 2004). After the transition from hard to soft state in 2011 (Rodríguez et al. 2011b), the source did not follow the standard q-track in the HID diagram (see e.g. Homan et al. 2001; Homan & Belloni 2005, and reference

therein) and, since March 2011, it remained trapped in an oscillatory state, similarly to what observed during the flaring states of GRS 1915+105 (Altamirano et al. 2011d).

As mentioned above (see section 4.1), the pseudo periodic bursts in the light curve of GRS 1915+105 reach the Eddington luminosity and are believed to be related to disc oscillations. The physics that drives these inner disc oscillations is connected with both the local Eddington limit and the radiation pressure instability. If the “heartbeat” oscillations seen from IGR J17091–3624 are interpreted as being due to the same mechanism as in GRS 1915+105 (as also supposed by Altamirano et al. 2011d), then the apparent “faintness” of IGR J17091–3624 remains unexplained unless to suppose a huge distance or an extremely low BH mass (Altamirano et al. 2011d).

In Section 4.1 we noted that that a reduction of the apparent luminosity up to an order of magnitude can also be achieved if the system is seen nearly edge on (for inclination angles < 75 degrees, Eggleton 1983). According to this idea and considering also the L/L_{Edd} ratio calculated for the different distance values, we can speculate that the source, probably, not only lies far from the Galactic bulge, in agreement with Rodríguez et al. (2011b), but it is observed at a high inclination angle as well. As also discussed in Section 4.1, this finding is not in contrast with the lack of eclipses in the source light curve. In fact, if the companion star is small, the eclipses can be undetected even for a high inclination angle, as for example in the case of the BHC XTE J1118+480 (see e.g. Wagner et al. 2001; McClintock et al. 2001).

We note that at present we cannot exclude that the faintness of IGR J17091–3624 is only due to a very large distance (> 20 kpc) or to the extremely low BH mass ($< 3M_{\odot}$), as suggested by Altamirano et al. (2011d). The large distance, unusual for low mass X-ray binaries generally concentrated in the Galactic bulge (Grimm et al. 2002), could agree with the hypothesis reported by Jonker & Nelemans (2004) that the distances of the LMXB could be affected by a systematic error due to misclassification of the companion star.

However recent results, reported by King et al. (2012), based on a *Chandra* observation campaign, support the hypothesis that IGR J17091–3624 is observed at high inclination angle. Future refined estimation of the distance and the BH mass of IGR J17091–3624 might help understand if GRS 1915+105 and IGR J17091–3624 are very similar objects simply observed at very different distances or inclination angles. We point out that the high inclination of the system is a possible scenario to explain the low luminosity of the source without invoking very large distances or extremely low BH masses that may challenge the Rhoades & Ruffini limit (Rhoades & Ruffini 1974).

Finally we suggest that, as in the case of GRS 1915+105, also IGR J17091–3624 might show a “quasi-persistent” outburst of the order of years. Thus the *INTEGRAL* and *Swift* observation campaign of the 2011 outburst probably caught the evolution of a transient BH in a persistent GRS 1915+105-like phase.

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